Action of Particle Films on the Biology and Behavior of Pear Psylla (Homoptera: Psyllidae)

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ABSTRACT Particle films with different properties have been developed for arthropod pest control. Two basic film types are hydrophobic and hydrophilic films. The hydrophilic film formulations differ in the amount and kind of spreader-sticker that is incorporated into the kaolin particles. The effects of particle film type (hydrophobic versus hydrophilic) and formulation (Surround versus Surround WP) on the biology and behavior of pear psylla, *Cacopsylla pyricola* (Foerster), were investigated on pear in a series of laboratory studies. Scanning electron microscopy determined that the number of particles that attached to the front tibia of adult psylla differed by particle formulation but the particle sizes were fairly uniform and ranged from 3.6 to 4.5 μm in diameter. Adults had difficulty grasping particle film-treated leaves, and this effect was influenced by film type and leaf surface. Choice and no-choice tests indicated that adult settling and oviposition were very low, regardless of film type or formulation. Under no-choice conditions, adult mortality was low, in part, because the adults were able to feed through all 3% particle films, but at reduced rates. However, the mortality of adults sprayed with 3% particle film solutions ranged from 22.2 to 62.5% within 72 h after treatment, and mortalities differed most between the hydrophilic formulations. Nymphs born on particle film-treated foliage incurred high mortalities ranging from 58.9 to 82.0% by the time they reached the fifth instar and were affected most by particle film type. Nymphal development was not affected by particle film type or formulation. Egg fertility and nymphal hatch also were unaffected by particle films. These studies determined that there are a number of biological effects particle films have on pear psylla beyond the deterrence of adult settling and oviposition.

KEY WORDS whitewash, kaolin, deterrent, repellent, physical barrier

PARTICLE FILM TECHNOLOGY IS a unique pest control option that protects plants from insect attack by creating a kaolin-based particle barrier on plant surfaces (Glenn et al. 1999). This technology was originally based on hydrophobic kaolin particle films but it was later found that either hydrophobic or hydrophilic kaolin particle films performed equally well as barriers to pear psylla, *Cacopsylla pyricola* (Foerster), infestations and the pear disease Fabraea leafspot (Puterka et al. 2000a, b). The commercial formulation soon shifted from hydrophobic to hydrophilic kaolin-based particle films. Hydrophilic particle films vary by formulation in that they contain either a liquid spreader-sticker that is added to the particles during tank mixing (M97–009 or Surround) or have spreaders-stickers incorporated into the particles as a dry formulation (Surround WP, Engelhard Corp., Iselin, NJ).

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Particle film barriers applied to plant foliage have two key effects on arthropod behavior and biology. Both hydrophobic M96-018 and hydrophilic Surround particle films have been shown to greatly reduce oviposition and adult settling of pear psylla on pear (Puterka et al. 2000a, b) and codling moth, *Cydia pomonella* (L.), on apple (Unruh et al. 2000). Surround WP also reduced adult settling and oviposition of the boll weevil, *Anthonomus grandis grandis* Boheman, on cotton buds (Showler 2002); silverleaf whitefly, *Bemisia argentifolii* Bellows & Perring, on melon (Liang and Liu 2002); *Homalodisca coagulata* (Say) on grape (Puterka et al. 2003); and others (Glenn and Puterka 2005).

The potential differences in the underlying mechanisms in how hydrophobic and hydrophilic films affect insect biology and behavior have received little study. The objective of this research was to investigate how hydrophobic and hydrophilic particle film types and different hydrophilic formulations affect the biology and behavior of pear psylla on pear.

Materials and Methods

The particle films used in this study were a hydrophobic film (M96-018) hydrophilic film A (Surround), and hydrophilic film B (Surround WP) that are manufactured by Engelhard Corp. (Iselin, NJ). The particle films are based on the same type of processed hydrous kaolin particle (1.0 ± 0.5 μm in diameter; R.C.P., unpublished data). The hydrophobic particle film contains kaolin particles that are surface treated with an organo-silicone oil to render the particles hydrophobic (M96-018). The hydrophilic films A and B differ in that hydrophilic film A has an oil-based spreader sticker, M03 (Engelhard Corp.), added to the Surround solution at a 1.25% (vol:vol), whereas hydrophilic film B has a dry oil-based spreader-sticker incorporated into the particles at ≈2 times the rate of hydrophilic film A to increase adhesion to foliage (R.C.P., unpublished data). These materials were chosen to provide comparisons between different particle film types, hydrophobic (M96-018) versus hydrophilic (Surround and Surround WP) films, and between hydrophilic formulations, hydrophilic film A (Surround) versus hydrophilic film B (Surround WP), on the biology and behavior of pear psylla. The particle films were applied at concentrations of 3% solids in water (wt:wt) as recommended by the manufacturer, although the ovicidal study compared 3 with 6% concentrations. The particle films were applied to plants by spraying them to runoff with a hand held sprayer. The pear psylla colony used in the experiments were collected from pear trees at the USDA–ARS Appalachian Fruit Research Station, Kearneysville, WV, and maintained on 'Bartlett' pear seedlings at 25°C in an environmental chamber with a photoperiod of 14:10 (L:D) h.

Particle Attachment to Psyllids. The size and amount of kaolin particles that attached to a psyllid's body when it encountered the film were quantified. An individual adult female psyllid was confined within a 10-mm-diameter by 50-mm-tall glass vial that was lined with a pear leaf that had been sprayed with a 3% particle film solution until thoroughly wetted and allowed to dry. The bottom of the vial also was lined with a 10-mm leaf disc treated with a particle film treatment to further ensure continuous contact with the film. Once the adult psyllid had been introduced into the vial, the vial was capped with a foam plug and left in an upright position for a 10-min exposure period. Afterward, the adult was removed and placed in a freezer until ready for imaging with a scanning electron microscope (SEM). The psyllids were air-dried and mounted with the ventral side upward to enable the tibia of the first leg to be scanned. The front tibia and tarsal area was of primary interest because the legs were one area where particles were observed to accumulate, and this area allowed multiple measurements to be taken. The number and diameter of the particles that attached to the front tibia was quantified by importing the digital SEM images into Corel Draw (Corel Corp., Ottawa, Ontario, Canada). Three 25.0-μm-diameter areas of the tibia were randomly selected, and the number and size of particles within each area were recorded. The measurements were calibrated in Corel Draw by using the micron bar scale that accompanied each SEM image, and the diameter of each particle was determined by averaging the length and width (Fig. 1). The experiment was a completely randomized design (CRD) with three replications.

Deterred Grasping of Leaf Surfaces. An adult psyllid's ability to grasp pear leaves treated with each of the three different particle films was compared with untreated leaves. Both sides of a pear leaf were sprayed with a 3% particle film solution and allowed to dry. An adult female psyllid was then placed on the upper side of the leaf with camel's-hair brush and allowed to move or settle upon the leaf surface for 30 s before the leaf was inverted for 10 s to determine whether the psyllid could remain on the leaf. This process was repeated on the under side of the leaf using a different psyllid. The percentage of individuals falling from the leaf was determined for each treatment and leaf side from 20 individuals observed per replication. The experiment was conducted as a CRD with four replications.

Choice Study: Adult Host Selection and Oviposition. Adults were placed in an arena and given a choice between particle film treated and untreated pear foliage to determine how particle films affected settling and oviposition. Pear seedling cuttings 20.0 cm in length were transferred to 20-ml glass vials filled with distilled water and then sealed with Parafilm. Cuttings treated with the hydrophobic film, hydrophilic film A and B, and an untreated control were placed in a 40.0-cm-tall by 15.0-cm-diameter cylinder cage arena made of Lexan (General Electric Corp., Fairfield, CT) that was topped with fine mesh screen. Ten adult psyllids of each sex were placed within the arena and observed every 24 h for a 3 d period. Data were recorded daily and included the percentages of adults that settled on each plant treatment, the total number of adults alive and number of eggs per plant. The experiment was a randomized complete block design (RCBD) with seven replications made over time.

Oviposition, Mortality, Honeydew Production, and Effects of Film Coverage in No-Choice Studies. Mating pairs of adult psylla were collected from the colonies and confined to the upper surface of the particle film-treated host and nonhost substrates by 2.0-cm-diameter clip-cages to determine how feeding, oviposition, and survival were affected. Pear seedling cuttings 20.0 cm in length were transferred to 20-ml glass vials filled with distilled water and sealed with Parafilm. Both pear seedling cuttings and glass slides were sprayed with 3% solutions of the hydrophobic film, hydrophilic films A and B, or both substrates were left untreated as controls. The particle film-treated and untreated microscope slides were included as host substrates to separate the effects of particles (treated slides) and starvation (untreated slide) on psylla mortality. A clip-cage was attached to a treated leaf, and the percentage of the leaf area covered by the particle films within each cage was visually estimated in increments of 10%. A mating adult pair was then transferred into the clip-cage by using an aspirator. Adult mortality, number of eggs, and honeydew production

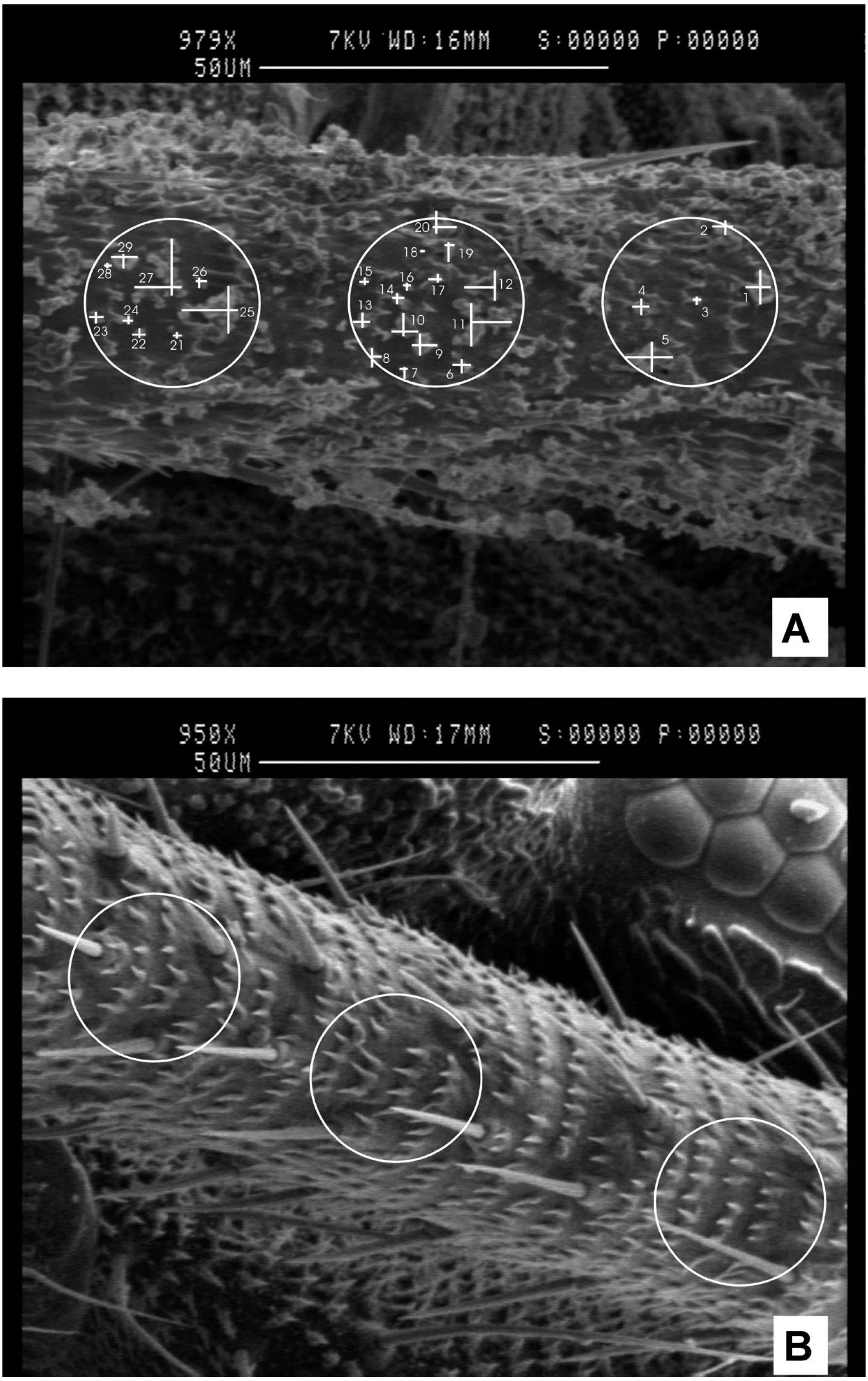

Fig. 1. (A) SEM image of the front tibia of a pear psylla adult that was caged on the hydrophobic film for 10 min. The 25.0-μm-diameter circles were randomly placed on the tibia and length and width measuring bars were generated using Corel Draw (Corel Corp.) to estimate the mean diameter of each particle. (B) SEM image of the front tibia of an adult from untreated foliage showing the lack of foreign particles.

were recorded daily for 4 d. Honeydew production was visually rated in comparison with the untreated control as a percentage of honeydew volume in 10% increments. The experiment was conducted as a randomized complete block design with 48 replications made over time.

Acute Mortality to Adults and Effect on Oviposition. Female adult psylla were sprayed with 3% solutions of the particles and transferred to untreated leaves to determine the acute effects of the sprays on adult mortality and oviposition. Five adult female psylla were placed in a petri dish and sprayed with either the hydrophobic film, hydrophilic films A or B, or water control by hand-held sprayer until wet. Afterward, the petri dish was covered to allow the adults to dry before they were individually caged on an untreated leaf cutting with the petiole placed in a water-filled vial. The clip-cage was sealed with a removable foam plug to facilitate counts on mortality and egg production 1, 24, 48, and 72 h after treatment. Mortality was based on an average from the five females per replicate. Oviposition was determined at the end of the study and egg counts were only made from those females that survived until the end of the 72-h period. The experiment was a RCBD with nine replications made over time.

Egg Mortality and Nymphal Eclosion and Survival. Particle films were applied to pear seedlings with psylla eggs deposited on the upper leaf surfaces to determine how particle films affected egg condition and mortality, and nymph eclosion and survival. Ten male and 10 female adult pear psyllids were placed in a cylinder cage containing a 20.0-cm-tall pear seedling and allowed to oviposit for a 3-d period. Afterward, the plant was sprayed with one of the three particle film treatments or with a water control. Particle film treatment concentrations of 3 and 6% were evaluated as two independent experiments. Clip-on cages 2.0 cm in diameter were then positioned over a group of 15 to 25 eggs for each treatment replication and observed daily for 14 d to ensure egg hatch in the untreated controls had ceased. Data recorded included egg desiccation and fertility, and nymphal mortality during eclosion and during settling at a feeding site. Nonviable eggs were those that did not show embryonic development (i.e., absence of characteristic eye spots within the egg appearing several days after oviposition). Eggs were considered desiccated when eye spots within the egg were present, but the egg had become shriveled in appearance. Unsuccessful eclosion occurred when nymphs died during the hatching process because they were unable to free themselves from the eggshell. Successful hatch was defined to occur if nymphs hatched, walked away from the egg, and established feeding as evidence of honeydew production. The experiment was a RCBD with seven replicates made over time.

Acute Mortality to Nymphs. Pear leaves infested with nymphs were sprayed with 3% solutions of the three particle films and compared with a water control to determine the acute mortality. A pear leaf with 25 second to third instars was sprayed with a 3% solution of one of the three particle film treatments or sprayed with water as a control. The spray was allowed to air dry before the leaf was placed in 100-mm petri dish that contained a 50.0-mm-diameter disc of #3 filter paper moistened with distilled water. The treated nymphs were observed for 3, 6, and 24 h after treatment and were probed with a fine hair brush to determine whether they were alive or dead. Observations were over a short time period to reduce the effect of other factors on mortality (e.g., starvation). The experiment was a RCBD with 10 replications made over time.

Chronic Effects on Nymphal Survival and Development. The effect of the three particle films on nymphal development was studied from egg hatch to the fifth instar. Pear psylla adults ($n = 20$) were caged upon several pear seedlings 30 cm in height and allowed to oviposit over a 3-d period. Afterward, the plants were held in a growth chamber until the eggs began to hatch. First instars ($n = 10$) were placed in a clip-cage that was attached to a 20-cm-tall potted pear seedling and allowed to settle for 2 h before the cage was removed. The infested leaf was then sprayed with a 6% solution of particle film or water as a control. The particle spray concentration of 6% was investigated because the 6% concentration had minimal effects on egg hatch and nymph survival in the egg mortality study. After the nymphs were sprayed, they were held for 24 h and observed for survival and one nymph was then selected per cage to observe development and survival. Approximately 40 cages per treatment were prepared so that at least 10 individual nymphs (replications) per treatment could be observed for development. The individual nymphs were examined daily for survival and presence of molted skins that were evidence of passage to the next instar. Observations were made daily over a 49-d period that enabled most nymphs to reach the fifth instar. The experimental design was a RCBD with 40 replications repeated in time.

Analysis. All percentage data in the experiments were arcsine square-root transformed before statistical analyses were made. The data from all experiments were subjected to analysis of variance (ANOVA) procedures and we used the Ryan–Einot–Gabriel–Welsch (REGWQ) multiple comparisons test ($P = 0.05$) to compare treatment means (SAS Institute 2001). An exception was for the no-choice experiment where the number replications varied because of adult escapes. Data from this experiment were analyzed by the general linear model (GLM) ANOVA (SAS Institute 2001).

Results

Particle Attachment to Psylla. The number of particles that attached to the tibia of adult females differed by particle film formulation (Table 1). Psylla adults accumulated nearly twice as many particles on their tibia when contacting the hydrophobic film and hydrophilic film A as opposed to hydrophilic film B-treated leaves ($F = 7.92$; df = 2, 6; $P = 0.02$). This relationship was reflected in the percentage of tibia area covered by these particles ($F = 4.70$; df = 2, 6; $P = 0.05$). The diameter of the particles that attached to the tibia were fairly uniform among the particle film treatments ($F = 0.32$; df = 2, 6; $P = 0.72$) and ranged between 3.6 and 4.5 μm (Fig. 1A). The front tibia of

Table 1. Mean (± SEM) number and size of particles that attached to the front tibia of adult pear psylla confined to pear leaves treated with 3% solutions of particle films for 10 min

Particle film	No. of particles	Particle diam. (μm)	% tarsal area covered
Hydrophobic film	25.3 ± 1.3a	4.1 ± 0.6a	65.8 ± 10.5a
Hydrophilic film A	22.0 ± 5.2a	4.5 ± 0.5a	57.9 ± 5.8a
Hydrophilic film B	13.5 ± 2.7b	3.6 ± 0.3a	27.1 ± 2.7b

Means within columns followed by the same letter were not significantly different at $P = 0.05$, REGWQ.

psyllids from the untreated controls (data not shown) were nearly void of particles (Fig. 1B).

Deterred Grasping of Leaf Surfaces. The particle film coating on pear leaves affected the psylla adult's ability to grasp the leaf (Table 2). Particle film treatment ($F = 84.75$; df = 3, 18; $P = 0.0001$), leaf surface ($F = 4.10$; df = 1, 18; $P = 0.05$), and treatment × surface interaction ($F = 26.8$; df = 2, 18; $P < 0.001$) were significant, indicating that different types of particle films affected psylla grasping differently on the upper and lower leaf surfaces. The hydrophobic film had a greater effect than the hydrophilic film A in impeding the psylla adult's ability to grasp both the upper and lower leaf surfaces.

Choice Study: Adult Host Selection and Oviposition. In the choice test, female adult psylla avoided settling and ovipositing on 3% particle film treated pear foliage (Table 3). Adult settling was significantly affected by treatment ($F = 29.7$; df = 3, 68; $P < 0.0001$) and not by time after application ($F = 0.6$; df = 2, 68; $P = 0.16$), yet there was a significant treatment × time interaction ($F = 2.9$; df = 6, 68; $P = 0.01$) that suggested adult settling preference change for each treatment over time. On 1 d, the hydrophobic film repelled 100% of the adults in comparison to ≈80% for the two hydrophilic films ($F = 34.6$; df = 3, 19; $P = 0.0001$). However, by the third day all of the particle film treatments were statistically equal in reducing adult numbers ($F = 9.2$; df = 3, 18; $P = 0.0006$) and oviposition ($F = 6.0$; df = 3, 18; $P = 0.004$) in comparison with the untreated control. Some adults settled on the cage sides, which resulted in the sum of treatment percentages to be <100% on any given day. Adult mortality was <2% regardless of the particle treatment.

Table 2. Mean (± SEM) percentage of adult psyllids unable to grasp the leaf and subsequently falling after being placed on 3% particle film-treated leaves for 30 s before the leaf was inverted for 10 s

Particle film	% falling from leaf	
	Upper surface	Lower surface
Hydrophobic film	100.0 ± 0.0a	70.0 ± 5.7a
Hydrophilic film A	70.0 ± 5.7b	45.0 ± 5.0b
Untreated control	0.0 ± 0.0c	0.0 ± 0.0c

Means within columns followed by the same letter are not significantly different at $P = 0.05$, REGWQ.

Table 3. Mean (± SEM) percentage of adults and no. of eggs on pear seedlings 3 d after adult female psylla were enclosed in an arena and provided a choice between leaves treated with a 3% particle film solutions and untreated control

Particle film type	% adults on pear seedlings			Eggs produced on day 3
	Day 1	Day 2	Day 3	
Hydrophobic film	0.0 ± 0.0c	0.0 ± 0.0c	0.0 ± 0.0b	0.0 ± 0.0b
Hydrophilic film A	20.6 ± 4.8b	17.2 ± 3.7b	3.7 ± 3.7b	7.8 ± 7.8b
Hydrophilic film B	17.7 ± 3.7b	13.4 ± 8.4b	13.7 ± 5.4b	10.0 ± 3.9b
Untreated control	47.5 ± 4.5a	44.1 ± 6.2a	36.4 ± 4.9a	69.6 ± 16.3a

Means within columns followed by the same letter are not significantly different at $P = 0.05$, REGWQ.

Oviposition, Mortality, Honeydew Production, and Effects of Film Coverage in No-Choice Study. Oviposition, mortality, and honeydew production of adults were significantly affected by particle film treatments (Table 4). Adult mortality was affected by treatment ($F = 6.71$; df = 3, 497; $P = 0.0002$), but not by time ($F = 2.01$; df = 3, 497; $P \leq 0.11$), or the treatment × time interaction ($F = 1.04$; df = 9, 497; $P = 0.41$). Honeydew production was affected by treatment ($F = 51.29$; df = 3, 497; $P < 0.0001$) and time effects ($F = 3.37$; df = 3, 497; $P < 0.01$), but the interaction of these effects was not significant ($F = 0.64$; df = 3, 475; $P < 0.54$). Therefore, mortality, honeydew, and oviposition were averaged over the 4-d study period (Table 4). The lack of a time × treatment interaction was a result of the relatively low rates of mortality in all treatments. Adult mortalities from the particle film treatments ranged from 0.7 to 10.5% with the hydrophobic film producing the highest mortalities. All of the adults placed on particle film treated and untreated glass slides died within the first day of treatment and did not produce eggs. The slide data were dropped from the analysis due to no differences in mortality between the starvation and particle effects.

Honeydew levels did not differ on the particle films and were reduced by 29.7 to 37% (Table 4). Oviposition was influenced by treatment ($F = 62.37$; df = 3, 475; $P < 0.0001$), time ($F = 3.50$; df = 3, 475; $P = 0.02$), and the interaction of these effects ($F = 5.32$; df = 9, 475; $P < 0.0001$). However, very few eggs were produced on the particle film treatments over the 4-d

Table 4. Mean (± SEM) percentage of leaf covered by particle films, adult mortality, numbers of eggs, and honeydew volume for female adults confined to 3% particle film treated pear foliage after 4 d in a no-choice experiment

Treatment	% leaf coverage	% mortality	Eggs oviposited	% honeydew vol[a]
Hydrophobic film	83.9 ± 2.4a	10.5 ± 2.3a	0.0 ± 0.01b	63.5 ± 1.4c
Hydrophilic film A	68.0 ± 2.9b	4.6 ± 1.6ab	0.0 ± 0.0b	69.0 ± 1.4b
Hydrophilic film B	82.4 ± 1.9a	0.7 ± 0.7b	0.2 ± 0.1b	70.3 ± 1.2b
Untreated control		0.0 ± 0.0c	6.9 ± 1.3a	100.0 ± 0.0a

Means within columns followed by the same letter are not significantly different at $P = 0.05$, REGWQ.

[a] Determined as a percentage of volume in comparison with the control.

Table 5. Mean (± SEM) acute mortality and oviposition of adult psylla that were sprayed with 3% particle film solutions and then transferred to untreated pear

Treatment	% cumulative mortality				Eggs oviposited after 72 h
	1 h	24 h	48 h	72 h	
Hydrophobic film	0.0 ± 0.0aB	14.3 ± 14.3aAB	22.2 ± 14.6bAB	57.1 ± 20.2aA	2.8 ± 1.5b
Hydrophilic film A	0.0 ± 0.0aB	22.2 ± 14.6aA	22.2 ± 14.6bA	22.2 ± 14.6bA	7.2 ± 3.6ab
Hydrophilic film B	12.5 ± 12.5aB	37.5 ± 18.2aAB	55.5 ± 17.3aA	62.5 ± 18.3aA	8.1 ± 4.5ab
Water control	0.0 ± 0.0aA	14.3 ± 14.3aA	14.3 ± 14.3bA	14.3 ± 14.3bA	13.3 ± 3.6a

Means within columns followed by the same lowercase letter or within rows followed by the same uppercase letter are not significantly different at $P = 0.05$, REGWQ.

period (Table 4). The significant treatment x time interaction for oviposition was due to a steady increase in rates of oviposition over time on the control leaves.

Particle film coverage of the leaf within the 2.0-cm-diameter clip-cages differed by treatment ($F = 12.23$; df = 2, 79; $P < 0.0001$). The hydrophobic film and hydrophilic film B coverage on leaves was similar (82.4–83.9%) in contrast to hydrophilic film A (68.0%) (Table 4). A significant treatment × coverage interaction occurred for mortality ($F = 2.67$; df = 4, 73; $P = 0.038$) and honeydew production ($F = 2.51$; df = 4, 73; $P = 0.048$) but not for oviposition ($F = 1.07$; df = 4, 73; $P = 0.379$). However, correlations for mortality, oviposition, and honeydew production with film coverage were not significant ($P \geq 0.21$), except for a low correlation between mortality and film coverage ($r^2 = 0.21$; df = 1, 127; $P = 0.014$). The lack of significant correlations between factors indicated that the leaf coverage effects had a minor influence on psylla mortality, oviposition, and honeydew production.

Acute Mortality to Adults and Effect on Oviposition. Adults sprayed with particle film solutions and then released on untreated pear foliage began showing mortality 48 h after treatment (Table 5). Mortality differed among treatments ($F = 3.7$; df = 3, 105; $P \leq 0.012$) and by time ($F = 4.8$; df = 3, 105; $P \leq 0.003$), but the interaction of these effects was not significant ($F = 0.6$; df = 9, 105; $P = 0.74$). None of the particle films showed immediate toxic effects to psylla adults 1 or 24 h after treatment. Yet, 48 h after treatment, hydrophilic film B produced a higher adult mortality than the other particle treatments. On 72 h after treatment, both the hydrophobic film and hydrophilic film B produced the highest mortality ranging from 57.1 to 62.5%, whereas adult mortality from contact with hydrophilic film A and the water control were comparatively low (14.3–22.2%). Egg production was significantly impacted by treatment ($F = 4.6$; df = 3, 24; $P \leq 0.04$); however, only the hydrophobic particle film reduces oviposition in comparison with the water control (Table 5).

Egg Mortality and Nymphal Eclosion and Survival. Particle film solutions were sprayed on pear leaves containing psylla eggs to determine their effects on egg viability and nymphal hatch over a 14-d period (Table 6). Particle films significantly affected egg desiccation in experiments 1 (3% applications) ($F = 3.4$; df = 3, 18; $P = 0.04$) and 2 (6% applications) ($F = 4.7$; df = 3, 18; $P = 0.02$). Egg viability was not influenced by particle films in experiments 1 ($F = 0.8$; df = 3, 18; $P = 0.50$) or 2 ($F = 1.2$; df = 3, 18; $P = 0.35$). The process of eclosion was not affected by the particle films in experiments 1 ($F = 0.7$; df = 3, 18; $P = 0.58$) or 2 ($F = 0.4$; df = 3, 18; $P = 0.79$). Furthermore, the percentage of nymphs that successfully hatched and established feeding was only slightly reduced by the hydrophobic particle film (15%) in relation to the control in both experiments 1 ($F = 3.8$; df = 3, 18; $P = 0.03$) and 2 ($F = 3.2$; df = 3, 18; $P = 0.04$).

Acute Mortality to Nymphs. Young nymphs infesting pear leaves incurred moderate levels of mortality soon after being sprayed with 3% solutions of particle films (Table 7). Nymphal mortalities were significantly affected by particle treatment ($F = 60.2$; df = 3, 99; $P \leq 0.0001$) and time after treatment ($F = 31.7$; df = 2, 99; $P \leq 0.0001$). There was a significant treatment × time interaction that resulted from increasing psylla mortalities that differed by treatment as the

Table 6. Mean (± SEM) percentage of damaged eggs and success of nymphs hatching from eggs ($n = 30$) 14 d after being oviposited onto pear leaves and then treated with 3 and 6% particle film solutions

Exp	Treatment	Egg		Nymph	
		% desiccated	% nonviable	% died while eclosing	% eclosed and feeding
1	3% Hydrophobic film	12.4 ± 3.8a	7.6 ± 3.4a	3.1 ± 3.1a	77.2 ± 9.9b
	3% Hydrophilic film A	7.7 ± 4.0b	5.0 ± 2.1a	0.6 ± 0.9a	86.5 ± 8.8ab
	3% Hydrophilic film B	8.5 ± 4.7ab	2.6 ± 3.6a	0.6 ± 0.9a	88.7 ± 10.2ab
	Water control	4.0 ± 2.9b	3.6 ± 2.8a	0.3 ± 0.2a	92.3 ± 12.8a
2	6% Hydrophobic film	16.2 ± 6.9a	2.9 ± 0.2a	2.7 ± 2.2a	78.1 ± 10.2b
	6% Hydrophilic film A	9.5 ± 3.3ab	1.9 ± 1.9a	0.9 ± 0.9a	87.6 ± 8.7ab
	6% Hydrophilic film B	9.2 ± 2.7ab	4.1 ± 3.3a	0.8 ± 0.8a	85.9 ± 9.3ab
	Water control	4.0 ± 1.9b	2.6 ± 0.9a	0.3 ± 0.3a	93.1 ± 10.9a

Means for each experiment that are within columns and followed by the same letter are not significantly different at $P = 0.05$, REGWQ.

Table 7. Mean (± SEM) mortality of nymphs 24 h after the nymphs and the leaves they infested were sprayed with 3% particle film solutions

Treatment	% cumulative mortality		
	3 h	6 h	24 h
Hydrophobic film	31.1 ± 7.2aA	46.3 ± 5.7abB	69.5 ± 6.8aC
Hydrophilic film A	39.5 ± 8.5aA	61.5 ± 8.6aB	83.6 ± 6.8aC
Hydrophilic film B	32.5 ± 7.4aA	44.3 ± 8.7bB	69.9 ± 9.9aC
Water control	1.8 ± 3.3bA	1.8 ± 3.3cA	1.8 ± 3.3bA

Means within columns followed by the same lowercase letter or means within rows followed by the same uppercase letter are not significantly different at $P = 0.05$, REGWQ.

experiment progressed ($F = 3.7$; df = 6, 99; $P \leq 0.002$). All particle film treatments produced nymphal mortalities higher than the control for all sample periods.

The particle film types inflicted about the same level of nymphal mortality in a given time period, although there were small significant differences in mortality between the hydrophobic and hydrophilic films 72 h after treatment. Nearly all of the nymphs that initially survived particle film treatments became agitated and moved to the untreated undersides of the leaves before the 3-h sampling period.

Chronic Effects on Nymphal Survival and Development. None of the particle film treatments had an effect on nymphal development ($F = 0.7$; df = 3, 77; $P = 0.57$) (Table 8), but the time required to pass from one instar to the next differed ($F = 101.2$; df = 4, 77; $P \leq 0.0001$). The developmental stage × treatment interaction ($F = 0.76$; df = 12, 77; $P = 0.68$) was significant, indicating that the particle film treatments were affecting each stage differently.

Pear psylla nymphs that emerged from eggs sprayed with 6% solutions of particle films were significantly affected by treatment ($F = 109.5$; df = 3, 114; $P \leq 0.0001$), stage of nymphal development ($F = 8.3$; df = 4, 114; $P \leq 0.001$), and treatment × stage interaction ($F = 2.6$; df = 12, 114; $P = 0.003$). Nymphal mortality generally increased with the successive stages of development (Table 9). The hydrophobic film produced ≈50% mortality during the processes of nymphal hatch and establishment of feeding by the first instar, whereas the hydrophilic films produced far lower first instar mortality that ranged from 18.7 to 30.0%. Differences in nymphal mortalities among the particle film types were not consistent for the third to fifth instars, although the hydrophobic film produced a significantly higher mortality (82.0%) compared with that of the hydrophilic film B (58.9%) for the fifth instar. The study was terminated by 49 d because the health of the plants had deteriorated. As a result, the data on adult emergence was incomplete and was dropped from the statistical analysis.

Discussion

Hydrophobic and hydrophilic particle films have been shown to be similar in how they repel pear psylla adults and reduce oviposition on pear in the field (Puterka et al. 2000b). Our research has determined that hydrophobic and hydrophilic particle films as well as formulations of hydrophilic particle films can differ

Table 8. Mean (± SEM) days for nymphs to pass from one instar to the next when hatched on pear seedlings treated with 6% particle films within a growth chamber at 25°C and a photoperiod of 14:11 (L:D) h

Life stage from[a]	Cumulative days to next stage			
	Hydrophobic film	Hydrophilic film A	Hydrophilic film B	Water control
Egg to first instar	8.2 ± 1.0dA	8.7 ± 0.6cA	8.4 ± 1.7cA	8.7 ± 0.7eA
First to second instar	10.5 ± 1.5dA	11.0 ± 0.4abA	12.2 ± 2.1bA	11.6 ± 0.7dA
Second to third instar	12.0 ± 0.0cA	12.5 ± 0.5abA	15.3 ± 1.7abA	14.2 ± 0.7cA
Third to fourth instar	14.0 ± 0.0bA	14.1 ± 0.8bA	19.2 ± 2.1aA	17.9 ± 1.4bA
Fourth to fifth instar	19.0 ± 0.0aA	20.8 ± 1.4aA	21.9 ± 3.2aA	23.5 ± 2.2aA

Means within columns followed by the same lowercase letter or means within rows followed by the same uppercase letter are not significantly different at $P = 0.05$, REGWQ.

[a] Number of days from egg deposition to the indicated instar.

Table 9. Mean (± SEM) percentage of mortality for nymphs that hatched and developed on 6% particle film treated pear seedlings within a growth chamber at 25°C and a photoperiod of 14:11 (L:D) h

Life stage from egg to[a]	Cumulative % mortality[b]			
	Hydrophobic film	Hydrophilic film A	Hydrophilic film B	Water control
First instar	49.1 ± 2.3cA	18.7 ± 3.6cC	30.0 ± 2.7cB	1.0 ± 1.0aD
Second instar	49.1 ± 2.3cA	17.1 ± 3.4cC	30.0 ± 2.7cB	1.6 ± 1.6aD
Third instar	49.1 ± 2.3cA	35.8 ± 4.7bC	48.8 ± 3.7bB	1.6 ± 1.6aD
Fourth instar	63.5 ± 3.0bA	38.1 ± 3.8bB	46.2 ± 4.1bB	2.5 ± 2.5aC
Fifth instar	82.0 ± 6.0aA	68.8 ± 4.4cAB	58.9 ± 3.2aB	2.5 ± 25aC

[a] Number of days from egg deposition to the indicated instar stage.

[b] Means within columns followed by the same lowercase letter or means within rows followed by the same uppercase letter are not significantly different at $P = 0.05$, REGWQ.

in how they affect pear psylla behavior and biology. Particle film type, specifically the hydrophobic film, had the greatest influence on pear psylla behavior and biology. The hydrophobic film had a greater impact than the hydrophilic films on an adult's ability to grasp plant surfaces, adult host preference, adult feeding rates, mortality in no-choice studies, oviposition after a brief contact with particle film, egg desiccation, nymphal hatch from treated eggs, and chronic mortality during nymphal development. The hydrophilic particle film formulations differed in the numbers of particles that attached to psylla tarsi, plant coverage, and acute adult mortality. There were a few studies where different particle film types or formulations had the same effects such as on the size of particles that attached to the insect, oviposition deterrence under choice and no-choice conditions, and chronic nymphal mortalities that were incurred while developing on particle film-treated leaves. None of the particle films affected egg survival or fertility or nymphal development on treated pear leaves.

We found the number of particles that attached to the tibia of adult psylla were highest with the hydrophobic film and hydrophilic film A. Higher amounts of oil-based spreader-stickers in the hydrophilic formulations increased particle film retention on pear foliage (Puterka et al. 2000b) that could account for differences in particle attachment between hydrophilic formulations. The numbers of particles that attach to insects is one measure of how strong particle-to-particle and particle-to-leaf adhesion becomes once a particle film spray dries. Particle adhesion is of particular significance to film function against insects in that fewer particles would be freed from the surface and attach to insects as they move upon more tightly bound films. In this manner, formulation ingredients can have a pronounced effect on the degree of particle attachment to insects. Surprisingly, the size of the particles that attached to the front tibia of psylla adults did not differ by particle type (hydrophilic versus hydrophobic) or hydrophilic formulation despite the differences in the number of particles that adhered to insects. The diameter of particles that attached to insects (3.6–4.5 μm in diameter) is an agglomeration of individual 1.0-μm-diameter kaolin particles that the films are base upon (Fig. 1A). The narrow size range of particles that attached to the psyllids tarsi indicates the tarsi had an affinity for particles of this range and that there may be a type of lock-and-key mechanism. Further research on particle attachment to other areas of the insect's bodies would contribute to a better understanding of particle film function and whether a lock-and-key mechanism is in play.

We demonstrated that adult psyllids have extreme difficulty in grasping particle film-treated surfaces apparently because the particles break away as the insects grasp the films. The hydrophobic film deterred grasping by a higher degree than the hydrophilic film A, even though both films had the same number of particles attaching to the tibia. We were not able to quantify the numbers of particles adhering to a psyllid's tarsi. Nevertheless, the data on grasping demonstrates that the hydrophobic film was more loosely bound to the leaf than hydrophilic film A. Our study determined that leaf surface influenced the degree that particle films affected psylla grasping. The undersides of pear leaves have trichomes, pronounced leaf veins, and stomates that could aid in grasping this surface. Particle films also have been shown to reduce walking speed in codling moth, larvae (Unruh et al. 2000). The loosely bound nature of these films and particle attachment to insects is a primary relationship that will likely differ with arthropod species and their adaptations to grasp the various plant and other surfaces in the niches they occupy.

Particle films were shown to deter adult settling and oviposition under choice and no-choice conditions. The choice experiment established that particle films are strongly rejected by pear psylla adults and that untreated pear foliage is preferred. Initially, the hydrophobic film had a greater effect on adult settling and oviposition over the hydrophilic films but this difference among particle films had diminished as the study progressed. Moreover, there were no differences among particle films in the no-choice study. Therefore, the various kinds of particle films seem to provide strong deterrence to settling and oviposition in pear psylla. There is essentially no information on the chemical and physical stimuli that influence oviposition. However, once a host has been selected, oviposition site location and preference can be influenced by leaf age and surface texture cues (Horton 1990, Horton and Krysan 1990). Even nonpreferred oviposition sites on a leaf could be made suitable by introducing an artificial mid-vein (Horton 1990). Based on this limited behavioral information, we propose that particle films act to reduce oviposition by structurally modifying or hiding plant surface relief with a particle film coating or through negative behavior stimuli where females determined that particle film-treated foliage is a poor host. Our laboratory results corroborate another study indicating that both hydrophobic and hydrophilic film A strongly deterred pear psylla oviposition and adult settling on pear in the field (Puterka et al. 2000a, b). A review of 13 laboratory and field studies on the various kinds of kaolin-based particle films and formulations that were tested against 14 insect species on 10 crops indicated that deterrence of insect settling and oviposition is the primary and most obvious action of particle films on insect behavior, regardless of film type or formulation (Glenn and Puterka 2005).

Honeydew production was used as an indication of pear psylla feeding inhibition in our study. Adult psylla did not settle and feed on particle film-treated pear under choice conditions. However, under no-choice conditions, pear psylla will feed through films and produce honeydew but at a reduced level. Only adults that survived after the first day after confinement on particle films produced honeydew, whereas those that died showed no evidence of feeding. Feeding inhibition also has been documented for *A. grandis grandis* on cotton (Showler 2002), *D. abbreviatus* on citrus

(Lapointe 2000), and the obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Knight et al. 2000).

Adult mortality varied by study and was low under no-choice conditions (0.65–10.5%) where adults were confined to particle film-treated pear leaves. In contrast, adults directly sprayed with particle films had relatively high mortalities (57.1–62.5) but only for the hydrophobic film and hydrophilic film B. Nymphs directly sprayed with particle films also displayed relatively high mortalities (69.5–83.6%). Low adult mortality in the no-choice study was due to the psyllids ability to feed through the films. The acute mortality for psylla that were directly sprayed with particle solutions progressed slowly for adults (48–72 h) in comparison with the short and almost immediate effects on nymphs (3–24 h). The slow progression of death for treated adults suggested that particle films had no immediate contact toxicity. Desiccation of *Tribolium* adults was implied for the hydrophobic film that produced ≥90% mortality, yet the hydrophilic film A had no effect on beetle mortality 5–7 d after treatment (Arthur and Puterka 2002). Hydrophilic films are apparently less absorbent to cuticular waxes; however, our data suggest that this property can be influenced by formulation. Other studies on the lethality of mineral particles to other insects found that several days are needed before sufficient cuticle abrasion or absorption occurs to cause death by desiccation (Alexander et al. 1944a, Kalmus 1944, Wigglesworth 1944, Hunt 1947, David and Gardiner 1950, Ebling and Wagner 1959). Nymphal mortality was rapid enough as to suggest another mechanism of action. The nymphs were of such small size that they were engulfed by the spray solution, making suffocation evident and death rapid. The surfactants or other formulation components of the particle films, especially those used in the hydrophilic formulations also could have had direct effects on the cuticle of psylla nymphs.

Particle film solutions of 3 and 6% solids that were applied directly to psylla eggs on pear foliage had a minimal effect on egg mortality and hatch. The particle films were expected to impede nymph eclosion because of the potential for emerging nymphs to be entangled by particles, yet, this did not occur. Our results agree with other studies that determined particle films lack ovicidal activity against the obliquebanded leafroller, Knight et al. (2000) and codling moth (Unruh et al. 2000) on apple.

Nymphs born on particle film-treated leaves did not have development affected even when higher rates of 6% particle film solutions were used. However, nymphs did incur high levels of mortality that increased as the developmental stages progressed. The nymphs must reestablish feeding sites after the molting process and those that were successful did develop normally. Yet, the particle films obviously interfered with a nymph's ability to move about and, in doing so, incurred significant mortalities in the process of attempting to locate suitable feeding sites. The hydrophobic particle film had a greater effect on nymphal mortality possibly due to the greater attachment of particles to their bodies. Reduced larval weight and survivorship also was documented in *C. rosaceana* (Knight et al. 2000).

The various film properties can affect the primary senses of taste, touch, smell, and vision of insects that also interact to produce a host acceptance or rejection response (Miller and Strickler 1984). The complex interactions between particle film properties and insect behaviors will obviously differ by insect species and the different host plants involved. There are likely many other indirect or less obvious effects that particle films have on insects beyond those described in this article. Particle film type, particularly the hydrophobic particles, was found to have a greater influence on psylla behavior and biology than the hydrophilic formulations. However, changes in the formulation of a hydrophilic film increased the activity to near that of the hydrophobic film in regard to particle attachment, adult, and nymphal mortalities, and adult grasping of the film. Recognizing how these film properties influence psyllid behavior and biology could provide opportunities to improve that action of particle films against this and other pest arthropods.

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